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Challenges in interaction modelling with digital human models – A systematic literature review of interaction modelling approaches

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ABSTRACT

Digital human models (DHM) allow for a proactive ergonomic assessment of products by applying different models describing the user-product interaction. In engineering design, DHM tools are currently not established as computer-aided ergonomics tools, since (among other reasons) the interaction models are either cumbersome to use, unstandardised, time-demanding or not trustworthy. To understand the challenges in interaction modelling, we conducted a systematic literature review with the aim of identification, classification and examination of existing interaction models. A schematic user–product interaction model for DHM is proposed, abstracting existing models and unifying the corresponding terminology. Additionally, nine general approaches to proactive interaction modelling were identified by classifying the reviewed interaction models. The approaches are discussed regarding their scope, limitations, strength and weaknesses. Ultimately, the literature review revealed that prevalent interaction models cannot be considered unconditionally suitable for engineering design since none of them offer a satisfactory combination of genuine proactivity and universal validity.

Practitioner summary: This contribution presents a systematic literature review conducted to identify, classify and examine existing proactive interaction modelling approaches for digital human models in engineering design. Ultimately, the literature review revealed that prevalent interaction models cannot be considered unconditionally suitable for engineering design since none of them offer a satisfactory combination of genuine proactivity and universal validity.

Abbreviations: DHM: digital human model; CAE: computer-aided engineering; RQ: research question

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Computer-aided ergonomics; digital human models; interaction modelling; engineering design; posture and movement prediction

1. Introduction

In engineering and industrial design, computer-aided ergonomics, in terms of a digital mock-up utilising digital human models (DHM), have become an important addition to classical user tests in terms of a physical or a mixed mock-up (Ahmed et al. 2019). A virtual mock-up for ergonomic assessments usually consists of a digital human model interacting with a digital product model in a given environment (Högberg et al. 2019). The idea behind this approach is to assess product ergonomics already in early (usually digital) design phases. Through the simulation of the interaction between the DHM as a representation of the prospective user and the product representing the design to evaluate, a specific use case can be examined. This approach is often referred to as proactive ergonomic assessment (Ahmed et al. 2019), which enables the product designer to run what-if scenarios in the early design phases (Bernard et al. 2019). Consequently and according to Chaffin (2005), the use of DHM may lead to improved physical product ergonomics while reducing the need for prototype building and ergonomics evaluation costs. Additionally, DHM enables an objective assessment of usually subjective measures, such as discomfort (Chevalot and Wang 2004).

In this paper, we want to focus on the application of physical multi-body human models, representing the human locomotor apparatus and aiming at the assessment of physical/physiological ergonomics in this regard. These DHM contain anthropometric measures, anatomical data or musculoskeletal capabilities to predict human response, body stress and so forth

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(Kanki et al. 2018). Anthropometric human models offer a realistic geometric representation of the human locomotor apparatus, to assess ergonomics in terms of space requirement analyses, reach analyses, visual analyses or manual handling tasks using ergonomic assessment methods like RULA (McAtamney and Nigel Corlett 1993) or EAWS (Schaub et al. 2013). Examples of industrially used anthropometric human models are Siemens Jack (Raschke and Cort 2019), RAMSIS (Wirsching 2019), Virtual Ergonomics by Dassault Systèmes (Charland 2019), IPS IMMA (Hanson et al. 2019)or EMA (Bauer et al. 2019). Biomechanical human models provide a detailed representation of the human musculoskeletal locomotor apparatus and allow dynamic analyses of human movement in order to compute biomechanical quantities (like a muscle- and joint-reaction forces). These biomechanical quantities can be used as a measure for ergonomic evaluation (Rasmussen 2005; Wagner, Reed, and Rasmussen 2007). Examples of prevalent biomechanical simulation frameworks are OpenSim (Seth et al. 2018), the AnyBody Modelling System (Damsgaard et al. 2006; Rasmussen 2019) and SANTOS (Abdel-Malek et al. 2019).

Conventionally, movement measurements (e.g. via motion capturing) are utilised to simulate the interaction of DHM with products. Those measurements, however, require subject studies using a physical or digital mock-up. Movement measurements using a physical mock-up resemble more of a reactive approach, assessing an already physically available product state (Ahmed et al. 2019). Alternatively, movement measurements can be performed by interacting with a digital mock-up, using virtual or augmented reality technology. Nevertheless, this approach still requires human subjects (Ahmed et al. 2019). In order to become a completely digital proactive computer-aided ergonomics tool, DHM consequently has to provide methods to predict the user-product interaction (Wolf, Binder, et al. 2019). These methods are referred to as proactive interaction modelling (Wartzack et al. 2019), task modelling (Högberg et al. 2019) or human behaviour modelling (Barone and Curcio 2004). In this paper, the term 'interaction' shall henceforth refer to physical user-product interaction using multibody DHM. As for the DHM, the interaction models as well have different depths of modelling detail and consequently different scopes.

According to various studies on DHM tools in engineering design, existing tools are either cumbersome to use (Ranger, Vezeau, and Lortie 2018), unstandardised (Paul and Wischniewski 2012), time-demanding or not trustworthy (Perez and Neumann 2015). All these points lead to a reduced acceptance, excluding especially the 'classical designer', without special ergonomic/human behaviour training, as potential tool user (Högberg 2009). Narrowing down the mentioned studies to interaction modelling, the following requirements can be derived for an interaction model to be suitable for engineering design:

1. A genuinely proactive/predictive approach, requiring little or no need for interaction specific prior knowledge or ergonomic expertise
2. A universally valid approach, which is generally applicable to a vast majority of products/use cases
3. A standardised, time-efficient and intuitive modelling procedure
4. A comprehensible straightforward modelling approach
5. The opportunity of data consistent embedment of the interaction modelling tools (DHM tools) in the computer-aided engineering (CAE) process

As it is our vision to establish computer-aided ergonomics in the design process (Wartzack et al. 2019; Wolf, Krüger, et al. 2019), we conducted a systematic literature review to identify, classify and examine existing proactive interaction models and to understand their scope, limitations, strength and weaknesses. Ultimately, we want to answer the following research questions (RQ):

RQ1: Which schematic models describing the user-product interaction exist and do they use a standardised terminology?

RQ2: Which proactive interaction modelling approaches exist?

RQ3: Which scope, limitations, strength and weaknesses do the proactive interaction modelling approaches have and are there an approach suitable for engineering design?

2. Methodology

2.1. Literature identification

In order to find significant literature, providing answers to the afore listed research questions we followed a systematic protocol (Figure 1), including an electronic searching and manual screening and clustering process. A literature search was performed using the Scopus database and search engine. The search was conducted on the titles and abstracts of papers in English language using the following search string: ((musculoske*) OR (anthropo*) OR (digital*) OR

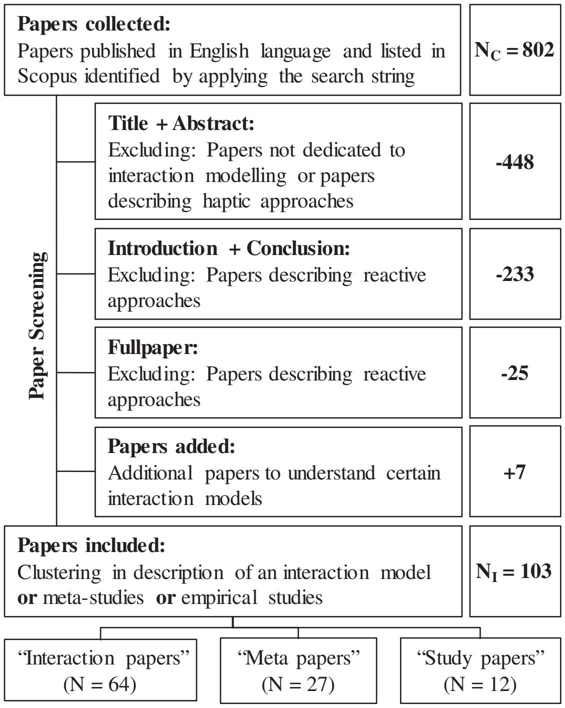

Figure 1. Systematic protocol for paper collection and screening.

(virtual*) OR (biomech*)) AND ((‘digital human*’) OR (‘digital man*’) OR (‘human model*’) OR (‘musculoske* model*’) OR (‘musculoske* simulat*’) OR (manikin*) OR (mannequin*) OR (‘man model*’)) AND ((ergonom*) OR (‘human factor*’) OR (usabili*) OR (comfor*)). This relatively generic search string was applied since it was our strategy to find computer-aided ergonomics approaches using digital human models and to select the papers dealing with interaction models subsequently. This strategy was chosen to increase the probability of finding papers on interaction modelling, since ‘interaction modelling’ as such is not explicitly mentioned in many publications.

According to this procedure, the total number of 802 papers were collected. Afterwards, the papers were screened and filtered by hand using predefined exclusion criteria. In the first step, all titles and abstracts were reviewed. Form the 802 papers, 448 papers were excluded as they are either not dedicated to interaction modelling using multibody DHM (e.g. excluding finite element or garment human models) or describe haptics modelling (e.g. grasping simulations), which is out of scope for this research. The remaining papers were screened in a second step by reviewing the introduction and conclusion. In this step, 233 papers were excluded as either they meet the exclusion criteria from step 1 or they describe a reactive approach (e.g. motion capturing or manual positioning). The remaining 121 papers were reviewed, by reading the full paper. In this last screening step, 25 papers were excluded based on the exclusion criteria of step 1 and 2. Seven papers, which were not included in the 802 collected papers, were added as they contain important additional information about interaction models, described in the identified literature. Finally, 103 papers were identified as significant literature to answer the RQ. Those papers were further clustered into three categories, which shall help to answer the RQ systematically. The cluster ‘interaction model papers’ contains 64 papers, which present or introduce a proactive interaction model. The cluster ‘meta papers’ contains 27 papers, which present Meta-Studies about the application of interaction models. The cluster ‘interaction study papers’ contains 12 papers, which present studies about interaction models. Table A1 in the Appendix A lists the identified significant literature in the respective clusters and highlights the papers that were manually added.

2.2. Literature analysis

The significant literature was separately analysed for each of the RQ. The objective of RQ 1 is to identify schematic user-product interaction models in the context of DHM and to review the accompanying terminology. Therefore, the papers of all three clusters were investigated. Based on the identified schematic models, we propose an abstracted model to unify the existing terminology and to provide a comprehensive schematic model for this research. RQ 2 is dedicated to identifying general interaction modelling approaches. Accordingly, the specific implementations of interaction models, grouped in the ‘interaction model papers’-cluster, were listed and (superficially) described. Subsequently, the papers of all three clusters were reviewed regarding classification schemas for interaction modelling approaches. The identified classification schemas were used to classify the specific interaction models based on their approach. Hereby, each paper was assigned to exactly one approach, although hybrid approaches exist. In case of ambiguity, the respective interaction model was assigned to the approach it most closely corresponds to. To provide answers to RQ3, the identified approaches were examined regarding their scope, limitations, strength and weaknesses. Hereby the papers of the ‘study-paper’-cluster, offered additional critical views on certain approaches. Eventually, the approaches were reviewed regarding their suitability for engineering design, taking the requirements listed in the introduction as a basis. Thereto, the underlying methodology of the approaches was evaluated, while the level of

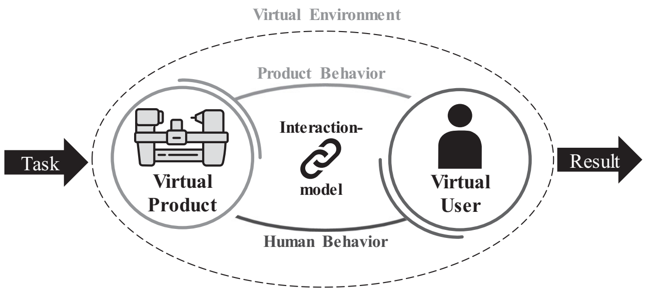

Figure 2. Schematic user–product interaction model for DHM.

implementation of the corresponding interaction models had no influence.

3. Results

3.1. Schematic user-product interaction models

The reviewed literature provides different schematic user–product interaction/man-machine interaction models for DHM. Based on the works of Pheasant and Haslegrave (2005) and Shackel (2009), Högberg et al. (2019) state, that the human-machine system is composed of four components: 'the users', 'the product', 'the tasks' and 'the environment'. They propose a DHM based framework to simulate these four components in mutual dependency to assess an 'evaluation scenario', which resembles a specific interaction. Bubb (2002) states that basic to all ergonomic layouts is a closed human-machine feedback loop consisting of 'a human operator', a 'machine' and an 'environment'. The loop starts with the definition of a 'task', which is the input to a simulation of the man-machine interaction causing a certain 'result'. By comparing the achieved 'result' with the initial 'task', the interaction model consists of a feedback control loop between man and machine. Seeger (2005) describes the interaction between a human and a product as a relationship of responsive perception and responsive behaviour in a given environment. Wartzack et al. (2019) extend this model by distinguishing the physical and psychical level of interaction. In addition to these generic models, Barone and Curcio (2004) and Chaffin (2002) propose to model observed 'human behaviour' or 'motor behavioural strategies'. All of these models use different perspectives and terminology. Nevertheless, they have the following entities in common: a (model of the) product/machine/workplace; a (model of the) human/worker/user; a (model of the) interaction and a (model of the) environment. In addition, all reviewed interaction models aim to predict/analyse interaction in the form of human movement or posture, partly with or without the corresponding forces. Figure 2 shows an abstraction of the different schematic models, unifying the partially heterogeneous prevalent terminologies.

The virtual product, user and environment are mutually independent models and serve as a carrier of information (e.g. dynamic characteristics) for the interaction model. The product behaviour contains a generic model describing a product's dynamics (or a lower level variation thereof, like kinematic states). The human behaviour contains a generic model describing the dynamics of a user (or a lower level variation thereof, like postures). Theoretically, three types of interaction models exist:

1. Predicting human behaviour as a function of a predefined product behaviour and the characteristics of the user, product and environment
2. Predicting product behaviour as a function of a predefined human behaviour and the characteristics of the user, product and environment
3. Predicting human behaviour and product behaviour in a mutually depended feedback loop, as a function of the characteristics of the user, product and environment

It is important to understand that there is a difference between this generic interaction model and a 'specific interaction'. A specific interaction is described via a task, containing the information (input variables) for the specific user-product interaction to be analysed. A task could contain product parameters defining a specific product, anthropometrical data defining a specific user, influential factors defining a specific environment and a set of position-time curves describing a specific product behaviour. The interaction model must transfer this information into a specific interaction, in this case, the human behaviour, which is the (ergonomically) assessable result. An interesting finding is that almost every interaction model described in the reviewed literature utilises the first interaction model type.

3.2. Interaction modelling approaches

The reviewed literature contains different approaches in order to predict human behaviour in terms of postures or movement either with or without the corresponding body-internal and external forces. Farahani et al. (2015) in line with Chaffin (2005) distinguishes two basic approaches of posture and movement prediction: The phenomenological approaches, predicting movement based on previously examined observations and the optimisation-based approaches, predicting movement using advanced optimisation algorithms (intended to work without the need of observations). In Carruth and Duffy (2008) the phenomenological approach is further divided into two strategies followed by the HUMOSIM group (Reed et al. 2006): Predicting movement by mimicking previously examined movement behaviour using mathematical and statistical modelling and predicting movement by modifying previously examined movements to a novel specific interaction. Farahani et al. (2015) further distribute the optimisation-based approaches in kinematics-based problems and dynamics and physiology-based problems. In general, the approaches can be distributed in posture prediction approaches and movement prediction approaches. Table 1 provides a classification of the interaction models described in the reviewed literature, based on their modelling approach and using the afore-described classification schemas. We assigned another level on top of the identified classes, further dividing approaches dedicated to predicting the human behaviour for a given product behaviour and approaches dedicated to finding the best possible product design for given human behaviour. Using these classification schemas, nine groups of interaction modelling approaches were identified (see Table 1).

The interaction models in Group 1 and 2 utilise an approach, which directly adapts/variates given joint-angle or end-effector trajectories, with the premise of finding the best possible fit between reference postures or movements from a database and kinematical constraints describing a specific interaction. The posture prediction models in Group 1 predominantly use regression algorithms (Lee et al. 2019; Li et al. 2019; Reed et al. 2002) or correlation methods (Barone and Curcio 2004) based on a posture database, to predict postures for novel specific interactions, via forward or inverse kinematic algorithms. Group 2 contains movement prediction algorithms based on the modification of measured movement trajectories. Park, Chaffin, and Martin (2004), Park, Singh, and Martin (2006), Alexopoulos et al. (2007), Ait El Menceur et al. (2015) and Monnier et al. (2006) propose motion modification algorithms in this regard. The interaction models in Group 3 utilise a mathematical parameterisation of specific postures based on kinematical constraints/measures (positions, orientations). Postures are predicted via a statistical description of the relationship between these kinematical measures and certain predictors, such as external forces (Hoffman, Reed, and Chaffin 2007; Hoffman, Reed, and Chaffin 2008), a specific task description (Hariri, Arora, and Abdel-Malek 2012) or discomfort effects (Chang and Tsai 2011). Lee et al. (2008) propose a posture prediction procedure, guiding the tool's users with statistical data. Group 4 contains interaction models, which statistically model movement data (usually based on motion capture data), in terms of computing hitherto unknown joint-angle or end-effector trajectories for given input variables. Several papers deal with the prediction of reach movement by utilising kinematic chains and inverse kinematic algorithms (Faraway and Reed 2007), Petri nets (Sun, Chung, and Lee 2010), neuronal networks (Lind et al. 2008), statistical modelling (Mavrikios et al. 2006), a modified minimum jerk criterion (Magistris et al. 2013) or an optimal control framework (Obentheuer et al. 2017). Lim, Martin, and Chung (2004) further examine the dynamic component of reach movements, especially with regard to the synchronicity of joint angles. Wagner, Kirschweng, and Reed (2009) and Wagner, Reed, and Chaffin (2010) observe and mathematically describe human behaviour in terms of foot motion/foot placement during manual material handling tasks. Kim et al. (2019) present movement prediction for ingress and egress movement using artificial neural networks. Wolf, Binder, et al. (2019) present movement prediction for lifting tasks using a regression model in combination with inverse kinematics. While those papers deal with very specific use cases, other papers introduce universal full-body movement prediction. Some of these papers (Tsimhoni and Reed 2007; Jeong, Wegner, and Noh 2010; Fuller, Reed, and Liu 2010) are devoted to the HUMOSIM Framework, which is composed of interconnected, hierarchical posture and movement prediction modules, containing statistical and mathematical models describing observed human behaviour (Reed et al. 2006). The HUMOSIM Framework is generally implementable in any DHM tool and was realised using a predecessor of Siemens Jack. Similar universal full-body movement predictions are presented by Fritzsche et al. (2011), Fritzsche et al. (2012) and Illmann et al. (2013) within the DHM tool EMA, by Kuo and Wang (2009), Kuo and Wang (2012) using a predecessor of Virtual Ergonomics by Dassault Systèmes and by Winter, Kronfeld, and Brunnett (2018) within the smart virtual worker DHM tool. These models, however, do not incorporate a module-based architecture. The interaction models classified in group 5–8 contain optimisation based approaches. These utilise a kinematic or dynamic objective function dedicated to optimise DHM kinematics (usually joint angle-time curves as variables), by minimising human performance measures (e.g. energy

Table 1. Classification of the interaction models described in the reviewed literature.

Classification of the interaction modelling approaches								
Human behaviour prediction								Product behaviour pred.
Phenomenological approaches				Optimisation-based approaches				
Movement modification		Statistic modelling		Dynamic simulation		Kinematic simulation		
Posture prediction	Movement prediction	Posture prediction	Movement prediction	Posture prediction	Movement prediction	Posture prediction	Movement prediction	
(Barone and Curcio 2004)	(Ait El Menceur et al. 2015)	(Chang and Tsai 2011)	(Faraway and Reed 2007)	(Kim et al. 2004)	(Farahani et al. 2015)	(Gragg, Yang, and Long 2010)	(Bohlin et al. 2012)	(Kuo and Chu 2005)
(Lee et al. 2019)	(Alexopoulos et al. 2007)	(Hariri, Arora, and Abdel-Malek 2012)	(Fritzsche et al. 2011)	(Ma et al. 2009)	(Kim, Abdel-Malek, Yang, and Nebel 2005)	(Gragg, Yang, and Long 2011)	(Delfs et al. 2012)	(Mergl et al. 2006)
(Li et al. 2019)	(Monnier et al. 2006)	(Hoffman, Reed, and Chaffin 2007)	(Fritzsche et al. 2012)	(Ma, Chablat, et al. 2010)	(Kim, Abdel-Malek, Yang, Farrell, et al. 2005)	(Hareesh et al. 2010)	(Hanson, Högberg, and Söderholm 2012)	(Patwardhan, Bloebaum, and Krovi 2005)
(Reed et al. 2002)	(Park, Chaffin, and Martin 2004)	(Hoffman, Reed, and Chaffin 2008)	(Fuller, Reed, and Liu 2010)	(Ma, Zhang, et al. 2010b)	(Abdel-Malek et al. 2009)	(Jung et al. 2009)	(Högberg et al. 2019)	
	(Park, Singh, and Martin 2006)	(Lee et al. 2008)	(Illmann et al. 2013)	(Ma et al. 2011)	(Yang et al. 2005)	(Rasmussen, Tørholm, and de Zee 2009)	(Mårdberg et al. 2014)	
			(Jeong, Wegner, and Noh 2010)	(Savin et al. 2017)			(Miehling et al. 2015)	
			(Kim et al. 2019)				(Pelliccia et al. 2016)	
			(Kuo and Wang 2009)				(Rasmussen 2005)	
			(Kuo and Wang 2012)				(Rasmussen, Boocock, and Paul 2012)	
			(Lim, Martin, and Chung 2004)				(Wolf and Wartzack 2018)	
			(Lind et al. 2008)					
			(Magistris et al. 2013)					
			(Mavrikios et al. 2006)					
			(Obentheuer et al. 2017)					
			(Reed et al. 2006)					
			(Sun, Chung, and Lee 2010)					
			(Tsimhoni and Reed 2007)					
			(Wagner, Kirschweng, and Reed 2009)					
			(Wagner, Reed, and Chaffin 2010)					
			(Winter, Kronfeld, and Brunnett 2018)					
			(Wolf, Binder, et al. 2019)					
Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9

consumption, muscle fatigue, discomfort etc.) subject to kinematic or dynamic constraints (e.g. dynamic equilibrium, predefined joint limits, end-effector paths and torque limits). Group 5 contains (exceptional) interaction models, which not primarily aim at the prediction of postures as such, but rather predict the variability of postures (Savin et al., 2017) or the effect of fatigue on certain postures. Kim et al. (2004) on the contrary, describe a (classical) dynamic reaching posture prediction. The further developed state of this interaction model (Kim, Abdel-Malek, Yang, and Nebel 2005; Kim, Abdel-Malek, Yang, Farrell, et al. 2005) enables reach movement prediction, utilising an inverse dynamic based optimisation problem. Hence, this model is part of group 6. Yang et al. (2005) and Abdel-Malek et al. (2009) present an advanced state of this model as the posture prediction and predictive dynamics tool included in the DHM-Framework SANTOS. Farahani et al. (2015) describe an inverse dynamic based optimisation called 'inverse-inverse dynamics' within the AnyBody Modelling System. The models listed in group 7 use kinematic optimisation formulations, such as multiple objective optimisation (Gragg, Yang, and Long 2010, 2011) and inverse kinematics (Jung et al. 2009; Rasmussen, Tørholm, and de Zee 2009; Hareesh et al. 2010) in order to predict postures from kinematic constrains. Group 8 contains papers presenting parts of the interaction model included in the IPS IMMA DHM-Framework (Högberg et al. 2016). This interaction model consists of a quasi-static optimisation, taking a comfort function, kinematic constraints (e.g. end-effector paths), contact forces and collision avoidance into account (Bohlin et al. 2012; Delfs et al. 2012; Hanson, Högberg, and Söderholm 2012; Mårdberg et al. 2014; Högberg et al., 2019). Miehling et al. (2015), Wolf and Wartzack (2018), Rasmussen and Christensen (2005), Rasmussen, Boocock, and Paul (2012) and Pelliccia et al. (2016) parameterise specific movements via kinematic constraints. By applying specific values (e.g. end-effector paths) to the kinematic constraints, the corresponding movement is predicted by applying (inverse) kinematic algorithms. Finally, the interaction models of group 9 contain a distinctly different approach, as they intend to compute the best possible product design for a fixed human behaviour. These specific publications, deal with the adjustment of car interiors to predefined postures considered as comfortable (Mergl et al. 2006; Kuo and Chu 2005; Patwardhan, Bloebaum, and Krovi 2005).

Besides the pure functionality, an interesting finding is that all interaction models describe an incremental procedure, hence simulating isolated specific interactions. Many interaction models utilise a high-level language to describe predefined tasks (increments), which can subsequently be interlinked to form a coherent interaction process (Fritzsche et al., 2011; Fritzsche et al. 2012; Illmann et al., 2013; Magistris et al. 2013; Högberg et al., 2019; Mårdberg et al. 2014; Winter, Kronfeld, and Brunnett 2018; Kuo and Wang 2009; Kuo and Wang 2012; Reed et al. 2006; Jeong, Wegner, and Noh 2010). Some interaction models provide a high-level language as a semantic interface to define a specific task (Kuo and Wang 2012; Jung et al. 2009). Few interaction models propose an integration of cognitive models (Fuller, Reed, and Liu 2010; Tsimhoni and Reed 2007) to substitute the need for manual task definition.

3.3. Analyses of interaction modelling approaches

The approach of finding the best possible product design for a predefined human behaviour strictly follows a user-centred strategy, designing a product 'around' the users instead of adapting an existing design to the users. This approach is limited by the need for having knowledge of the most ergonomic movement or posture in advance for a given use case. Since these are seldom known, most of the approaches focus on finding human behaviour for a given design, comparing different design alternatives.

Within these, the phenomenological approaches in general target the accurate prediction of specific use cases (e.g. reach movement or ingress/egress movement). Consequently, they do not necessarily require the user to have prior knowledge to model a specific interaction, as the observed information about human behaviour is provided by the underlying mathematical model. Thus, movement or postures can be predicted very accurately, as long as they stay inside the parameter space of the observations. Extrapolating from the parameter space is afflicted with the risk of predicting dynamically inconsistent or unbalanced movements, characterised by discontinuous position-time curves and non-sustainable postures. With other words, these models can solely predict validly what has been measured/observed before. Hereby, movement modification algorithms tend to be more precise but also more bound to the experimental data, while the statistical modelling tends to be more flexible with the risk to be less precise. Both approaches nevertheless are not universally applicable, unless a huge amount of data has been collected, like for the Humosim framework (Reed et al. 2006). However, even those interaction models are restricted to their parameter space and have limitations when it comes to the prediction of postures or movement dependent of external forces or individualities between specific users (e.g. regarding anthropometry, strength or agility). Hoffman, Reed, and Chaffin (2007, 2008) examine the influence of external forces on postures, showing the experimental effort necessary to universally model human behaviour when considering additional dimensions.

The optimisation-based approaches in general focus on the deployment of a universal posture or movement prediction in order to bypass a lack of experimental data or to substitute the need for experimental data as a whole. A distinct advantage of the optimisation-based approaches is the possibility of considering the influence of external forces, individualities between specific users or any other kinematic or dynamic constraints in the prediction algorithms. This universality on the other side involves the disadvantage that it requires the user to have prior knowledge in form of assumptions (e.g. a movement's duration), start solutions (posture or movements) or kinematic/dynamic constraints (e.g. end-effector paths) to describe a specific interaction. Even use cases which allow for a deduction of end-effector paths from the product behaviour, require additional assumptions and constraints incorporating prior knowledge (Farahani et al. 2015; Rasmussen and Christensen 2005; Miehling et al. 2015). Björkenstam et al. (2016) state in accordance with Wolf, Binder, et al. (2019), that some use cases require the consideration of dynamic effects in the movement prediction algorithms (e.g. predicting the utilisation of inertia forces in manual handling tasks). Kinematic optimisation-based approaches lack this possibility. Dynamic optimisation-based approaches, on the contrary, allow for the consideration of dynamic effects but are very complex to set up and highly demand modelling expertise as well as computational time. Thus, dynamic interaction predictions are even more restricted to the specific use case it was designed for.

Predicting postures reduces the complexity in interaction modelling, by excluding the time dimension. When reducing an ergonomic assessment to postures, however, it is important to keep in mind that for some interactions a postural simulation may not be sufficient (Monnier et al. 2006; Wagner, Reed, and Rasmussen 2007). In general, all interaction models intend to model postures and movement as 'realistic' as possible. This often involves the assumption that there is the one 'correct' solution for each specific interaction. Only few interaction models take the variability of movement (Savin et al., 2017), the effect of fatigue (Ma, Chablat, et al. 2010; Ma et al. 2011; Ma et al. 2009; Ma, Zhang, et al. 2010), different movement strategies (Ait El Menceur et al. 2015) or the movement adaptation due to discomfort effects (Chang and Tsai 2011) into account. In addition, an exact definition/prediction of the end effectors' positions is crucial for ergonomic assessment, as Wegner and Reed (2011) show for the definition of standing locations.

A comparison of all these findings with the defined requirements listed in the introduction reveals that various interaction models provide a standardised, time-efficient and intuitive modelling procedure as well as a comprehensible straightforward modelling approach. Additionally, many interaction models offer the opportunity of data consistent embedment in the CAE process, although it is solely implemented for a few. These requirements partially depend on the level of implementation of the corresponding interaction models. From a pure methodological point of view, however, the reviewed interaction models either require the user to have or gather prior knowledge/ergonomic expertise or are restricted to specific use cases. Thus, neither of them meets both requirements regarding a genuinely proactive/predictive approach and a universally valid approach. As a consequence, none of the reviewed interaction models is considered unconditionally suitable for engineering design.

3.4. Resolving the research questions

The literature study revealed answers to the raised research questions, which are essentially summarised next:

> RQ1: Different schematic user-product interaction models, with different perspectives, scopes and terminology are prevalent in the existing literature. Yet these models share common similarities, which allow for a deduction of an abstract schematic model.
>
> RQ2: Nine distinct proactive interaction modelling approaches, could be classified based on the reviewed literature. The vast majority of the interaction models predict human movement or posture with or without consideration of the corresponding moments and forces, using phenomenological or optimisation-based approaches.
>
> RQ3: Each approach has a distinct scope, with accompanying limitations, strength and weaknesses. In summary, neither of the reviewed interaction models is considered unconditionally suitable for engineering design, since none of them provides a combination of a genuinely proactive/predictive approach and universally valid approach.

4. Discussion

On a schematic level, the user-product interaction is often introduced as a feedback loop between user and product. The review of prevalent interaction models revealed a more rigid dependency, where the feedback loop is commonly restricted to an iterative optimisation of the human behaviour for a fixed product behaviour. The proposed schematic user–product interaction model provides an abstract top-level view on interaction modelling. Although not quantitatively validated, the schematic model was suitable to describe all reviewed interaction models. Thus, we are confident that this schematic model may help researchers to better understand the relevant entities of DHM interaction modelling, as well as their mutual dependencies.

The classification of interaction models provides a good overview about the prevalent approaches, although we want to underline that the classification needs to be understood as a general orientation rather than a distinct delimitation since many hybrid approaches exist. To name few examples, some optimisation-based approaches contain previously examined observations in terms of kinematical constraints or start solutions, for example, Rasmussen and Christensen (2005) or Miehling et al. (2015), while some phenomenological approaches utilise optimisation algorithms, for example, Park, Chaffin, and Martin (2004). Nevertheless, the classification may help researchers to decide which interaction modelling approach is suitable for their research. Additionally, it may support DHM-Tool users to identify the best fitting interaction model for a specific ergonomic assessment.

Ultimately, this research is devoted to an examination of existing interaction models in the context of applicability/suitability for engineering design. One identified key factor is genuine proactivity/predictivity. To include the 'classical designer' as potential tool user it is important that an interaction model does not require special ergonomic/human behaviour expertise. Technically speaking, the interaction models need to be capable of predicting human behaviour with as less input as possible. The second identified key factor is universal validity. To be generally applied in engineering design, the interaction model needs to cover the largest possible and widest heterogeneous amount of interaction possibilities with products. This leads to a conflict of objectives since as many interaction possibilities as possible should be predicted with as little input as possible. The fact that this contradiction is still unresolved explains why DHM tools are not yet widely used for computer-aided ergonomics in engineering design. This identified research gap may serve as a call for action for future research.

Lastly, it should be emphasised that the chosen literature review methodology cannot terminally ensure, that all existing interaction models were discovered since solely Scopus has been used as a database, the search string may not be comprehensive, and the manual screening process might be biased due to predisposition of the researchers. Nevertheless, a comparison with the recently published state-of-the-art book DHM and Posturography (Scataglini and Paul 2019) did not reveal any unknown or new approaches.

5. Conclusion and outlook

The literature review revealed that prevalent interaction models cannot be considered unconditionally suitable for engineering design since none of them offers a satisfactory combination of genuine proactivity/predictivity and universal validity. The question that should be investigated in the future is whether it is possible to find such a combination. The authors see two possibilities to address this issue. One way is to conduct research regarding advanced optimisation algorithms (e.g. using optimal control) or advanced phenomenological-based algorithms (e.g. using machine learning), which are capable of predicting human behaviour with little input. The other possibility is to find a useful compromise that focuses on selected aspects of human behaviour. This could be the prediction of postures under consideration of kinematic and dynamic constraints (e.g. end-effector positions and external forces) or the prediction of micro- or gross motor-movement. Such a compromise would limit the universal validity of the prediction but still provide useful information on many questions. The benefit of such a restriction is, that it limits the design space of the human behaviour to be predicted. Thus, prevalent interaction models may be applicable, when properly combined. The authors see great potential in a combination of phenomenological and optimisation-based approaches. An optimisation-based approach enables an extrapolation from the parameter space, whilst a phenomenological approach could provide a start solution and constraints for the optimisation algorithm.

The authors will conduct future research towards the development of a phenomenological optimisation-based posture prediction approach. We are confident to find a suitable interaction model to contribute to the establishment of DHM as computer-aided ergonomics tools in engineering and industrial design.

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Wirsching, H.-J. 2019. “Human Solutions RAMSIS.” In *DHM and Posturography*, edited by S. Scataglini and G. Paul, 49–55. London, UK: Academic Press.

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Wolf, A., D. Krüger, J. Miehling, and S. Wartzack. 2019. “Approaching an Ergonomic Future: An Affordance-Based Interaction Concept for Digital Human Models.” *Procedia CIRP* 84: 520–525. doi: 10.1016/j.procir.2019.03.198.

Wolf, A., and S. Wartzack. 2018. “Parametric Movement Synthesis: Towards Virtual Optimisation of Man-Machine Interaction in Engineering Design.” In *Design 2018*, edited by D. Marjanović, M. Štorga, S. Šk, N. Bojčetić, and N. Pavković, 941–952. Glasgow, UK: Design Society.

Yang, J., T. Marler, H. Kim, K. Farrell, A. Mathai, S. Beck, K. Abdel-Malek, J. Arora, and K. Nebel. 2005. *Santos^{TM}: A New Generation of Virtual Humans* (SAE Technical Papers 2005-01-1407). Warrendale, PA: SAE International.

Appendix A.

Table A1. List of the reviewed literature in the respective clusters in alphabetical order.

	Reviewed literature
Cluster: Interaction model papers	
1	Abdel-Malek, K., Arora, J., Yang, J., Marler, T., Beck, S., Swan, C., Law, L.F., Kim, J., Bhatt, R., Mathai, A., Murphy, C., Rahmatalla, S., Patrick, A. and Obusek, J. (2009), "A physics-based digital human model", *International Journal of Vehicle Design*, Vol. 51 No. 3/4, p. 324. 10.1504/IJVD.2009.027960.
2	Ait El Menceur, M.O., Pudlo, P., Gorce, P. and Lepoutre, F.-X. (2015), "A numerical tool to simulate the kinematics of the ingress movement in variably-dimensioned vehicles for elderly and/or persons with prosthesis", *International Journal of Industrial Ergonomics*, Vol. 47, pp. 9–29. 10.1016/j.ergon.2015.01.014.
3	Alexopoulos, K., Mavrikios, D., Pappas, M., Ntelis, E. and Chryssolouris, G. (2007), "Multi-criteria upper-body human motion adaptation", *International Journal of Computer Integrated Manufacturing*, Vol. 20 No. 1, pp. 57–70. 10.1080/09511920500233749.
4	Barone, S. and Curcio, A. (2004), "A computer-aided design-based system for posture analyses of motorcycles", *Journal of Engineering Design*, Vol. 15 No. 6, pp. 581–595. 10.1080/09544820410001731146.
5	(Manually Added): Bohlin, R., Delfs, R., Hanson, L. and Carlson, J.S. (2012), "Automatic Creation of Virtual Manikin Motions Maximizing Comfort in Manual Assembly Processes", in Jack Hu, S. (Ed.), *Technologies and Systems for Assembly Quality, Productivity and Customization: Proceedings of the 4th CIRP Conference on Assembly Technologies and Systems*, Michigan, USA, pp. 209–212.
6	Chang, C.-M. and Tsai, J.J.P. (2011), "Ergonomic Designs Based on Musculoskeletal Models", in *2011 11th IEEE International Conference on Bioinformatics and Bioengineering: 24-26 Oct. 2011 Taichung, Taiwan*, IEEE Computer Society, Los Alamitos, CA, pp. 112–116. 10.1109/BIBE.2011.24.
7	Delfs, N., Gustafsson, S., Carlson, J.S., Bohlin, R. and Mårdberg, P. (2012), "Comparison of algorithms for automatic creation of virtual manikin motions", in Duffy, V.G. (Ed.), *Advances in applied human modelling and simulation, Advances in human factors and ergonomics series*, Online-ausg, CRC Press, Boca Raton.
8	Farahani, S.D., Bertucci, W., Andersen, M.S., Zee, M.d. and Rasmussen, J. (2015), "Prediction of crank torque and pedal angle profiles during pedaling movements by biomechanical optimization", *Structural and Multidisciplinary Optimisation*, Vol. 51 No. 1, pp. 251–266. 10.1007/s00158-014-1135-6.
9	Faraway, J. and Reed, M.P. (2007), "Statistics for Digital Human Motion Modeling in Ergonomics", *Technometrics*, Vol. 49 No. 3, pp. 277–290. 10.1198/004017007000000281.
10	Fritzsche, L., Jendrusch, R., Leidholdt, W., Bauer, S., Jäckel, T. and Pirger, A. (2011), "Introducing ema (Editor for Manual Work Activities) – A New Tool for Enhancing Accuracy and Efficiency of Human Simulations in Digital Production Planning", in Duffy, V.G. (Ed.), *Digital human modelling: Third international conference, ICDHM 2011, held as part of HCI international 2011, Orlando, FL, USA July 2011 proceedings*, *Lecture notes in computer science*, Vol. 6777, Springer Berlin Heidelberg; Imprint: Springer, Berlin, Heidelberg, pp. 272–281. 10.1007/978-3-642-21799-9_31.
11	Fritzsche, L., Leidholdt, W., Bauer, S., Jäckel, T. and Moreno, A. (2012), "Interactive production planning and ergonomic assessment with Digital Human Models–introducing the Editor for Manual Work Activities (ema)", *Work*, Vol. 41, pp. 4428–4432. 10.3233/WOR-2012-0741-4428.
12	Fuller, H.J.A., Reed, M.P. and Liu, Y. (2010), "Integrating physical and cognitive human models to represent driving behavior", in *HFES 2010: Proceedings of the Human Factors and Ergonomics Society 54th annual meeting September 27 -October 1, 2010, San Francisco, California, USA*, Human Factors and Ergonomics Society, Santa Monica, CA. 10.1518/107118110 × 12829369833169.
13	Gragg, J., Yang, J. and Long, J.D. (2010), "Digital Human Model for Driver Seat Adjustment Range Determination", *SAE Technical Paper 2010-01-0386*. 10.4271/2010-01-0386.
14	Gragg, J., Yang, J. and Long, J.D. (2011), "Optimisation-based approach for determining driver seat adjustment range for vehicles", *International Journal of Vehicle Design*, Vol. 57 No. 2/3, p. 148. 10.1504/IJVD.2011.044716.
15	Hanson, L., Högberg, D. and Söderholm, M. (2012), "Digital test assembly of truck parts with the IMMA-tool–an illustrative case", *Work*, Vol. 41, pp. 2248–2252. 10.3233/WOR-2012-0447-2248.
16	Hareesh, P.V., Kimura, T., Adachi, S. and Thalmann, D., "An ergonomic evaluation engine for conceptual design stage using anthropometric digital human models", in *Proceedings of DESIGN 2010, the 11th International Design Conference*.
17	Hariri, M., Arora, J. and Abdel-Malek, K., "Optimization-Based Prediction of Aiming and Kneeling Military Tasks Performed by a Soldier", in *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Design Engineering Division, pp. 661–671. 10.1115/DETC2012-71166.
18	Hoffman, S.G., Reed, M. and Chaffin, D.B. (2009), "Postural Behaviors during One-Hand Force Exertions", *AE Int. J. Passeng. Cars - Mech. Syst. 1(1):1136-1142*, Vol. 1 No. 1, pp. 1136–1142. 10.4271/2008-01-1915.
19	Hoffman, S.G., Reed, M.P. and Chaffin, D.B. (2007), "Predicting Force-Exertion Postures from Task Variables", *SAE Technical Paper 2007-01-2480*. 10.4271/2007-01-2480.
20	Högberg, D., Castro, P.R., Mårdberg, P., Delfs, N., Nurbo, P., Fragoso, P., Andersson, L., Brolin, E. and Hanson, L. (2019), "DHM Based Test Procedure Concept for Proactive Ergonomics Assessments in the Vehicle Interior Design Process", in Bagnara, S., Tartaglia, R., Albolino, S., Alexander, T. and Fujita, Y. (Eds.), *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018): Volume V: Human Simulation and Virtual Environments, Work With Computing Systems (WWCS), Process Control*, Springer International Publishing, Cham, pp. 314–323. 10.1007/978-3-319-96077-7_33.
21	Illmann, B., Fritzsche, L., Leidholdt, W., Bauer, S. and Dietrich, M. (2013), "Application and Future Developments of EMA in Digital Production Planning and Ergonomics", in Duffy, V.G. (Ed.), *Digital human modelling and applications in health, safety, ergonomics, and risk management: 4th International Conference, DHM 2013, held as part of HCI International 2013, Las Vegas, NV, USA, July 21-26, 2013, LNCS sublibrary. SL 3, Information systems and application, incl. Internet/Web and HCI*, Vol. 8026, Springer, Berlin, pp. 66–75. 10.1007/978-3-642-39182-8_8.
22	Jeong, S., Wegner, D.M. and Noh, S. (2010), "Validation of an ontology-based approach for enhancing human simulation in general assembly environments", in Ao, S.I. (Ed.), *World Congress on Engineering: WCE 2010 30 June — 2 July, 2010, Imperial College London, London, U.K*, Newswood Ltd; International Association of Engineers, Hong Kong.
23	Jung, M., Cho, H., Roh, T. and Lee, K. (2009), "Integrated Framework for Vehicle Interior Design Using Digital Human Model", *Journal of Computer Science and Technology*, Vol. 24 No. 6, pp. 1149–1161. 10.1007/s11390-009-9287-3.
24	Kim, J.H., Abdel-Malek, K., Mi, Z. and Nebel, K. (2004), "Layout Design using an Optimization-Based Human Energy Consumption Formulation", *SAE Technical Papers 2004-01-2175*. 10.4271/2004-01-2175.

(*continued*)

Appendix A.Table A1. Continued.

Reviewed literature	
Cluster: Interaction model papers	
25	Kim, J.H., Abdel-Malek, K., Yang, J., Farrell, K. and Nebel, K. (2005a), "Optimization-Based Dynamic Motion Simulation and Energy Expenditure Prediction for a Digital Human", *SAE Technical Papers 2005-01-2717*. 10.4271/2005-01-2717.
26	Kim, J.H., Abdel-Malek, K., Yang, J. and Nebel, K. (2005b), "Motion Prediction and Inverse Dynamics for Human Upper Extremities", *SAE Technical Papers 2005-01-1408*. 10.4271/2005-01-1408.
27	Kim, Y., Soo Choi, E., Seo, J., Choi, W.-S., Lee, J. and Lee, K. (2019), "A novel approach to predicting human ingress motion using an artificial neural network", *Journal of Biomechanics*, Vol. 84, pp. 27–35. 10.1016/j.jbiomech.2018.12.009.
28	Kuo, C.-F. and Chu, C.-H. (2005), "An online ergonomic evaluator for 3D product design", *Computers in Industry*, Vol. 56 No. 5, pp. 479–492. 10.1016/j.compind.2005.02.002.
29	Kuo, C.-F. and Wang, M.-J. (2009), "Motion generation from MTM semantics", *Computers in Industry*, Vol. 60 No. 5, pp. 339–348. 10.1016/j.compind.2009.01.006.
30	Kuo, C.-F. and Wang, M.-J.J. (2012), "Motion generation and virtual simulation in a digital environment", *International Journal of Production Research*, Vol. 50 No. 22, pp. 6519–6529. 10.1080/00207543.2011.653698.
31	Lee, B., Jin, T., Lee, S.-H. and Saakes, D. (2019), "SmartManikin", in Brewster, S., Fitzpatrick, G., Cox, A.L. and Kostakos, V. (Eds.), *CHI 2019: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems May 4-9, 2019, Glasgow, Scotland, UK*, The Association for Computing Machinery, New York, New York, pp. 1–13. 10.1145/3290605.3300814.
32	Lee, J.H., Kwon, B.K., Kyung, G. and Nussbaum, M.A. (2008), "Predicting Driving Postures and Seated Positions in SUVs Using a 3D Digital Human Modeling Tool", *SAE Technical Papers 2008-01-1856*. 10.4271/2008-01-1856.
33	Li, H., Zhao, D., Ma, X. and Jin, X. (2019), "Predictive model of tractor driving posture considering front and rear view", *Biosystems Engineering*, Vol. 185, pp. 64–75. 10.1016/j.biosystemseng.2019.03.010.
34	Lim, S., Martin, B.J. and Chung, M.K. (2004), "The effects of target location on temporal coordination of the upper body during 3D seated reaches considering the range of motion", *International Journal of Industrial Ergonomics*, Vol. 34 No. 5, pp. 395–405. 10.1016/j.ergon.2004.05.002.
35	Lind, S., Krassi, B., Viitaniemi, J., Kiviranta, S., Heilala, J. and Berlin, C. (2008), "Linking ergonomics simulation to production process development", in Jefferson, T. (Ed.), *Proceedings of the 2008 Winter Simulation Conference, Miami, Florida, USA*, Winter Simulation Conference, Miami, Florida, USA, pp. 1968–1973. 10.1109/WSC.2008.4736290.
36	Ma, L., Chablat, D., Bennis, F., Hu, B. and Zhang, W. (2010a), "Integrating Digital Human Modeling Into Virtual Environment for Ergonomic Oriented Design", in *Proceedings of the ASME World Conference on Innovative Virtual Reality–2010: Presented at ASME 2010 World Conference on Innovative Virtual Reality, May 12-14, 2010, Ames, Iowa, USA*, American Society of Mechanical Engineers, New York, N.Y., pp. 203–210. 10.1115/WINVR2010-3729.
37	Ma, L., Chablat, D., Bennis, F., Zhang, W., Hu, B. and Guillaume, F. (2011), "Fatigue evaluation in maintenance and assembly operations by digital human simulation in virtual environment", *Virtual Reality*, Vol. 15 No. 1, pp. 55–68. 10.1007/s10055-010-0156-8.
38	Ma, L., Zhang, W., Chablat, D., Bennis, F. and Guillaume, F. (2009), "Multi-objective optimisation method for posture prediction and analysis with consideration of fatigue effect and its application case", *Computers and Industrial Engineering*, Vol. 57 No. 4, pp. 1235–1246. 10.1016/j.cie.2009.06.003.
39	Ma, L., Zhang, W., Fu, H., Guo, Y., Chablat, D., Bennis, F., Sawanoi, A. and Fugiwara, N. (2010b), "A framework for interactive work design based on motion tracking, simulation, and analysis", *Human Factors and Ergonomics in Manufacturing*, Vol. 20 No. 4, pp. 339–352. 10.1002/hfm.20178.
40	Magistris, G. de, Micaelli, A., Evrard, P., Andriot, C., Savin, J., Gaudez, C. and Marsot, J. (2013), "Dynamic control of DHM for ergonomic assessments", *International Journal of Industrial Ergonomics*, Vol. 43 No. 2, pp. 170–180. 10.1016/j.ergon.2013.01.003.
41	(Manually Added): Mårdberg, P., Carlson, J.S., Bohlin, R., Delfs, N., Gustafsson, S., Högberg, D. and Hanson, L. (2014), "Using a formal high-level language and an automated manikin to automatically generate assembly instructions", *International Journal of Human Factors Modelling and Simulation*, Vol. 4 No. 3/4, p. 233. 10.1504/IJHFMS.2014.067180.
42	Mavrikios, D., Karabatsou, V., Alexopoulos, K., Pappas, M., Gogos, P. and Chryssolouris, G. (2006), "An approach to human motion analysis and modelling", *International Journal of Industrial Ergonomics*, Vol. 36 No. 11, pp. 979–989. 10.1016/j.ergon.2006.08.001.
43	Mergl, C., Bubb, H., Vogt, C. and Kress, H. (2006), "Ergonomic Layout Process for a Driver Working Place in Cars", *SAE Technical Papers 2006-01-2313*. 10.4271/2006-01-2313.
44	Miehling, J., Schuhhardt, J., Paulus-Rohmer, F. and Wartzack, S., "Computer Aided Ergonomics Through Parametric Biomechanical Simulation", in *Proceedings of the ASME 2015 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*. 10.1115/DETC2015-46064.
45	Monnier, G., Renard, F., Chameroy, A., Wang, X. and Trasbot, J. (2006), "A motion simulation approach integrated into a design engineering process", *SAE Technical Papers 2006-01-2359*. 10.4271/2006-01-2359.
46	Obentheuer, M., Roller, M., Björkenstam, S., Berns, K. and Linn, J., "Human like motion generation for ergonomic assessment -A muscle driven digital human model using muscle synergies", in *ECCOMAS Thematic Conference on Multibody Dynamics*.
47	Park, W., Chaffin, D.B. and Martin, B.J. (2004), "Toward Memory-Based Human Motion Simulation: Development and Validation of a Motion Modification Algorithm", *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, Vol. 34 No. 3, pp. 376–386. 10.1109/TSMCA.2003.822965.
48	(Manually Added): Park, W., Singh, D. and Martin, B.J. (2006), "A memory-based model for planning target reach postures in the presence of obstructions", *Ergonomics*, Vol. 49 No. 15, pp. 1565–1580. 10.1080/00140130600834598.
49	Patwardhan, S.S., Bloebaum, C.L. and Krovi, V.N. (2005), "Using Anthropometric Modeling for Optimal Ergonomic Considerations in Automobile Interior Design", *SAE Technical Papers 2005-01-2718*. 10.4271/2005-01-2718.
50	Pelliccia, L., Klimant, F., Santis, A. de, Di Gironimo, G., Lanzotti, A., Tarallo, A., Putz, M. and Klimant, P. (2017), "Task-based Motion Control of Digital Humans for Industrial Applications", in Teti, R. (Ed.), *10th CIRP International Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16*, Procedia CIRP, pp. 535–540. 10.1016/j.procir.2016.06.057.
51	Rasmussen, J., Boocock, M. and Paul, G. (2012), "Advanced musculoskeletal simulation as an ergonomic design method", *Work*, Vol. 41 No. SUPPL.1, pp. 6107–6111. 10.3233/WOR-2012-1069-6107.
52	Rasmussen, J. and Christensen, S.T. (2005), "Musculoskeletal Modeling of Egress with the AnyBody Modeling System", *SAE Technical Papers 2005-01-2721*. 10.4271/2005-01-2721.
53	Rasmussen, J., Tørholm, S. and Zee, M.d. (2009), "Computational analysis of the influence of seat pan inclination and friction on muscle activity and spinal joint forces", *International Journal of Industrial Ergonomics*, Vol. 39 No. 1, pp. 52–57. 10.1016/j.ergon.2008.07.008.

(*continued*)

Appendix A.Table A1. Continued.

	Reviewed literature
Cluster: Interaction model papers	
54	Reed, M.P., Faraway, J., Chaffin, D.B. and Martin, B.J. (2006), "The HUMOSIM Ergonomics Framework: A New Approach to Digital Human Simulation for Ergonomic Analysis", *SAE Technical Papers 2006-01-2365*. 10.4271/2006-01-2365.
55	Reed, M.P., Manary, M.A., Flannagan, C.A.C. and Schneider, L.W. (2002), "A statistical method for predicting automobile driving posture", *Human Factors*, Vol. 44 No. 4, pp. 557–568. 10.1518/0018720024496917.
56	Savin, J., Gilles, M., Gaudez, C., Padois, V. and Bidaud, P. (2017), "Movement Variability and Digital Human Models: Development of a Demonstrator Taking the Effects of Muscular Fatigue into Account", in Duffy, V.G. (Ed.), *Advances in applied digital human modelling and simulation: Proceedings of the AHFE 2016 International Conference on Digital Human Modelling and Simulation*, *Advances in Intelligent Systems and Computing*, Vol. 481, Springer, [Switzerland], pp. 169–179. 10.1007/978-3-319-41627-4_16.
57	Sun, T.-L., Chung, P.-Y. and Lee, P.-S. (2010), "Rapid Interaction Specification in DHM-Included VE to Support Virtual Design Ergonomic Evaluation", in Huang, G.Q., Mak, K.L. and Maropoulos, P.G. (Eds.), *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology*, *Advances in Soft Computing*, Vol. 66, Springer, Berlin, pp. 497–506. 10.1007/978-3-642-10430-5_38.
58	Tsimhoni, O. and Reed, M.P. (2007), "The Virtual Driver: Integrating Task Planning and Cognitive Simulation with Human Movement Models", *SAE Technical Papers 2007-01-1766*. 10.4271/2007-01-1766.
59	Wagner, D.W., Kirschweng, R.L. and Reed, M.P. (2009), "Foot motions in manual material handling transfer tasks: a taxonomy and data from an automotive assembly plant", *Ergonomics*, Vol. 52 No. 3, pp. 362–383. 10.1080/00140130802376034.
60	Wagner, D.W., Reed, M.P. and Chaffin, D.B. (2010), "The development of a model to predict the effects of worker and task factors on foot placements in manual material handling tasks", *Ergonomics*, Vol. 53 No. 11, pp. 1368–1384. 10.1080/00140139.2010.523482.
61	Winter, M., Kronfeld, T. and Brunnett, G. (2018), "Semi-Automatic Task Planning of Virtual Humans in Digital Factory Settings", *Computer-Aided Design and Applications*, Vol. 16 No. 4, pp. 688–702. 10.14733/cadaps.2019.688-702.
62	Wolf, A., Binder, N., Miehling, J. and Wartzack, S. (2019), "Towards Virtual Assessment of Human Factors: A Concept for Data Driven Prediction and Analysis of Physical User-product Interactions", in *Proceedings of the 22nd International Conference on Engineering Design (ICED19)*, Cambridge University Press, pp. 4029–4038. 10.1017/dsi.2019.410.
63	(Manually Added): Wolf, A. and Wartzack, S. (2018), "PARAMETRIC MOVEMENT SYNTHESIS: TOWARDS VIRTUAL OPTIMISATION OF MAN-MACHINE INTERACTION IN ENGINEERING DESIGN", in Marjanović, D., Štorga, M., Škec, S., Bojčetić, N. and Pavković, N. (Eds.), *Design 2018*, Faculty of Mechanical Engineering and Naval Architecture; Design Society, Zagreb, Glasgow, pp. 941–952. 10.21278/idc.2018.0400.
64	Yang, J., Marler, T., Kim, H., Farrell, K., Mathai, A., Beck, S., Abdel-Malek, K., Arora, J. and Nebel, K. (2005), "Santos^{TM}: A New Generation of Virtual Humans", *SAE Technical Papers 2005-01-1407*. 10.4271/2005-01-1407.
Cluster: Meta papers	
1	Badler, N.I., Lee, P., Phillips, C., Otani, E.M. and Haug Edward J. (1990), "Jack interactive human model", *American Society of Mechanical Engineers, Design Engineering Division (Publication) DE*, Vol. 22.
2	Bonney, M.C., Blunsdon, C.A., Case, K. and Porter, J.M. (1979), "Man-machine interaction in work systems", *International Journal of Production Research*, Vol. 17 No. 6, pp. 619–629. 10.1080/00207547908919641.
3	Bubb, H. (2002), "Computer aided tools of ergonomics and system design", *Human Factors and Ergonomics in Manufacturing*, Vol. 12 No. 3, pp. 249–265. 10.1002/hfm.10013.
4	Carruth, D.W. and Duffy, V.G. (2008), "Integrating cognitive and digital human models for virtual product design", in Chebykin, O.Y., Bedny, G. and Karwowski, W. (Eds.), *Ergonomics and Psychology*, CRC Press.
5	Chaffin, D.B. (2002), "On simulating human reach motions for ergonomics analyses", *Human Factors and Ergonomics in Manufacturing*, Vol. 12 No. 3, pp. 235–247. 10.1002/hfm.10018.
6	Chaffin, D.B. (2005), "Improving digital human modelling for proactive ergonomics in design", *Ergonomics*, Vol. 48 No. 5, pp. 478–491. 10.1080/00140130400029191.
7	Chaffin, D.B. (2007), "Human motion simulation for vehicle and workplace design", *Human Factors and Ergonomics in Manufacturing*, Vol. 17 No. 5, pp. 475–484. 10.1002/hfm.20087.
8	Chen, P., Xia, P.J., Lang, Y.D. and Yao, Y.X. (2009), "A Human-Centered Virtual Assembly System", *Applied Mechanics and Materials*, 16-19, pp. 796–800. 10.4028/www.scientific.net/AMM.16-19.796. . . . .
9	Hogberg, D. (2009), "Digital human modelling for user-centred vehicle design and anthropometric analysis", *International Journal of Vehicle Design*, Vol. 51 No. 3/4, p. 306. 10.1504/IJVD.2009.027959.
10	Hogberg, D., Backstrand, G., Lamkull, D., Hanson, L. and Ortengren, R. (2008), "Industrial customisation of digital human modelling tools", *International Journal of Services Operations and Informatics*, Vol. 3 No. 1, p. 53. 10.1504/IJSOI.2008.017705.
11	Honglun, H., Shouqian, S. and Yunhe, P. (2007), "Research on virtual human in ergonomic simulation", *Computers and Industrial Engineering*, Vol. 53 No. 2, pp. 350–356. 10.1016/j.cie.2007.06.027.
12	Kingsley, E.C., Schofield, N.A. and Case, K. (1981a), "A computer aid for man machine modelling", *Proceedings of the 8th Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH 1981*, pp. 163–169. 10.1145/800224.806802.
13	Kingsley, E.C., Schofield, N.A. and Case, K. (1981b), "A computer aid for man machine modelling", *Comput Graphics (ACM)*, Vol. 15 No. 3, pp. 163–169. 10.1145/965161.806802.
14	Liu, Y., Zhou, T., Li, N., Li, H. and Huang, T. (2019), "Digital Human Modeling for Performance Evaluation During Marine Vehicle Operation", in Long, S. and Dhillon, B.S. (Eds.), *Man-Machine-Environment System Engineering: Proceedings of the 18th International Conference on MMESE*, *Lecture Notes in Electrical Engineering*, Vol. 576, Springer Singapore, Singapore, pp. 769–777. 10.1007/978-981-13-8779-1_87.
15	Miehling, J., Wolf, A. and Wartzack, S. (2019), "Musculoskeletal Simulation and Evaluation of Support System Designs", in Karafillidis, A. and Weidner, R. (Eds.), *Developing Support Technologies: Integrating Multiple Perspectives to Create Assistance That People Really Want*, *Biosystems and Biorobotics Ser*, Vol. 23, Springer, Cham, pp. 219–227. 10.1007/978-3-030-01836-8_21.
16	Mochimaru, M. (2017), "Digital Human Models for Human-Centered Design", *Journal of Robotics and Mechatronics*, Vol. 29 No. 5, pp. 783–789. 10.20965/jrm.2017.p0783.
17	Mochimaru, M., Kouchi, M., Miyata, N., Tada, M., Yoshida, Y., Aoki, K., Kawachi, K. and Motomura, Y. (2006), "Dhaiba: Functional Human Models to Represent Variation of Shape, Motion and Subjective Assessment", *SAE Technical Papers 2006-01-2345*. 10.4271/2006-01-2345.
18	Mollard, R., Vernay, J., Coblentz, A. and Hennion, P.-Y. (1999), "Ergodata: A Dedicated Database System for Digital Human Modeling and Ergonomic Studies", *SAE Technical Papers 1999-01-1888*. 10.4271/1999-01-1888.
19	Patel, T., Sanjog, J. and Karmakar, S. (2016), "Ergonomics Perspective in Agricultural Research: A User-Centred Approach Using CAD and Digital Human Modeling (DHM) Technologies", *Journal of The Institution of Engineers (India): Series A*, Vol. 97 No. 3, pp. 333–342. 10.1007/s40030-016-0162-2.

(*continued*)

Appendix A.Table A1. Continued.

Reviewed literature	
Cluster: Interaction model papers	
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